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INTEGRATED ANALYSIS AND APPLICATIONS

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SUMMARY

An overview is presented of current research activities which, in a broad context, are focused on the development and verification of integrated structural analysis and optimal design capabilities for advanced aerospace propulsion and power systems. The overview encompasses a variety of subject areas including (1) composite materials, (2) advanced structural analysis, (3) constitutive modeling, (4) computational simulation, (5) probabilistic analysis, and (6) multidisciplinary optimization. Typical results are presented which illustrate the benefit and utility of the emerging technologies as applied to propulsion and power system structures.

INTRODUCTION

The perpetual "ideology" of propulsion system design is to achieve increasingly higher levels of performance and, at the same time, longer life cycles. This presents difficult challenges for the structural engineer to provide, in the most cost-effective manner possible, designs that are lightweight, fuel-efficient, durable, and reliable. Successful accomplishment of these tasks depends on the availability of structural analysis and design tools that are capable of accurately and efficiently representing the complex geometries, material responses, loading histories, and boundary conditions typical of propulsion system structures.

With an objective to address these needs, the Structures Division of NASA Lewis Research Center is conducting a variety of research and development activities. It is the purpose here to provide an executive overview of a sample of those efforts from which particularly promising technologies have recently emerged or which represent the most current programmatic emphasis. The overview encompasses a variety of subject areas including

(1) Composite materials - analytical models (composite mechanics), integrated computational capabilities, and experimental characterization of composite structural behavior and durability for polymer, metal, and ceramic matrix systems

(2) Advanced structural analysis - algorithms and numerical schemes for more accurate and efficient inelastic analyses

(3) Constitutive modeling - theoretical model formulation and experimental characterization of thermoviscoplastic material behavior

(4) Computational simulation - engine structures from single components to assemblies and up to an entire engine system subjected to simulated test-stand and mission load histories

(5) Probabilistic structural analysis - quantification of uncertainty in geometry, material, load, and boundary conditions on structural response for reliability assessment

(6) Structural optimization - implementation of mathematical optimization and multidisciplinary analyses to provide streamlined, autonomous optimal design systems

In some instances, typical results are presented which illustrate the benefit and utility of these emerging technologies as applied to propulsion system structures.

INTEGRATED COMPOSITES ANALYZER

The numerous properties needed for composite structural analysis and design, combined with the difficulty and expense of obtaining experimental measurements of these properties, has motivated development of the Integrated Composites Analyzer (ICAN) computer code (refs. 1 and 2). The ICAN code incorporates the necessary composite mechanics to perform point analysis of multilayered fiber composite laminates subjected to arbitrary hygrothermal environments. Input variables to ICAN include constituent material system(s), laminate configuration, fabrication conditions, and service environment. The ICAN code predicts virtually all composite hygral, thermal, and mechanical properties necessary to perform structural analysis and has proven to be an effective tool for preliminary design of composite structures. Confidence in the predictive capabilities of ICAN has been established through favorable comparisons with experimental data obtained for a variety of composite systems in extreme hygrothermal environments (fig. 1).

COMPUTATIONAL SIMULATION OF COMPOSITE SANDWICH STRUCTURE

A recent enhancement of the ICAN computer code has extended its applicability to composite sandwich structural configurations. This new feature of ICAN was demonstrated recently in the preliminary design of composite antenna reflector structure for the Advanced Communications Technology Satellite (refs. 3 and 4). In this application, parametric studies were conducted to determine desirable face sheet and honeycomb core configurations necessary to provide thermal distortion-free structure in the simulated space environment. A critical variable of interest in the investigation was the effective thermal expansion coefficient for a candidate configuration and its variation over the range of simulated hygrothermal conditions representative of the space environment (fig. 2). The approximate methodology developed to simulate thermostructural behavior of sandwich composites has been demonstrated to be highly effective for preliminary design purposes (ref. 5).

COMPREHENSIVE EVALUATION OF COMPOSITE DURABILITY

In an effort to characterize durability and damage tolerance of composite structures, a comprehensive research program is ongoing to develop analytical models with experimental verification. The analytical models including composite mechanics, composite failure theories, and cumulative damage models are incorporated into the Composite Durability Structural Analyzer (CODSTRAN) computer code (refs. 6 and 7). The CODSTRON code assesses durability in terms of defect growth and damage progression on a ply-by-ply basis through an incremental/iterative solution scheme. The companion experimental program is conducted by using the unique Real-Time Ultrasonic C-Scan (RUSCAN) facility where sequential graphic images are created from acoustic emissions taken in real time of a specimen as it is incrementally loaded to fracture. The excellent correlation achieved between the CODSTRAN predictions and experimental observations (fig. 3) enhances confidence in the ability to analytically assess durability of composite structures.

STRUCTURAL ANALYSIS FOR HIGH-TEMPERATURE COMPOSITES

The mechanical performance and structural integrity of high-temperature composites is ultimately governed by the behavior of the constituents (i.e., fiber, matrix, and interphase) locally. This local constituent behavior is dynamic and complex because of various nonlinearities associated with, for example, (1) large excursions in stress/strain, (2) temperature-dependent material properties, and (3) time-dependent effects. In the analysis/design of a composite structure, then, it is essential to be able to track this local behavior and to relate its effects on global structural response. An integrated approach has been developed to provide this capability by incorporating constituent material models and cumulative damage models, composite mechanics (micro and macro), and global structural analysis (fig. 4). The cyclic arrangement depicts the computational effort for each load increment of a nonlinear structural analysis. Material nonlinearity is treated at the constituent level, where the present material model defines a time-temperature-stress dependence of a constituent's mechanical and thermal properties at a given instant in its "material history space." Characteristic properties of the composite, at the various levels of simulation, are approximated on the basis of the instantaneous constituent properties by using composite mechanics models. This process termed "synthesis" results in a point description of equivalent pseudohomogeneous properties for the composite which can be used for subsequent global structural analysis. In a similar manner global response variables can be decomposed into localized response, again at the various levels of simulation. This integrated approach has recently been implemented into the Metal Matrix Composite Analyzer (METCAN) computer code (ref. 8). An example of the type of information obtained from METCAN is the nonlinear stress-strain response to monotonic loading at room temperature for tungsten/copper composites (unidirectional) of two different fiber volume fractions (fig. 5). Exhibited in the results is the excellent correlation between METCAN predicted response and experimental observations.

METAL MATRIX COMPOSITE TECHNOLOGY DEVELOPMENT

Through a cooperative effort between the Structures and Materials Divisions, Lewis Research Center is providing a unique contribution to the development of metal matrix composite (MMC) technology (fig. 6). The Materials Division is capable of fabricating thin-walled tubular MMC specimens (ref. 9), which are then tested by the Structures Division under multiaxial conditions at elevated temperatures (ref. 10). From these tests the necessary material functions and parameters can be determined to support theoretical formulation of viscoplastic constitutive models (ref. 11). The constitutive models, in turn, are implemented into advanced structural analysis computer codes to predict the response of MMC components subjected to complex thermomechanical loading histories. These analyses provide important information to aid the engineer in making design decisions for actual aerospace propulsion system applications.

ADVANCED INELASTIC STRUCTURAL ANALYSIS METHODS

The desire for increased performance and efficiency of gas turbine engines has led to designs having more severe operating cycles (i.e., higher pressures and temperatures). The general result has been an exhibited decrease in engine durability with associated increase in maintenance costs, particularly in the hot section, where more hostile environments accelerate component wear and damage. Reliable, cost-effective design to achieve prescribed durability requires effective (i.e., accurate and efficient) structural analysis tools that account for the complex geometries, loading conditions, and forms of nonlinear material response that are characteristic of these components in their operating environment (fig. 7). A broad spectrum of structures technology development carried out under the Hot Section Technology (HOST) Program (ref. 12) is addressing these needs. These efforts encompass three key elements: (1) constitutive modeling, which includes theoretical formulation of viscoplastic constitutive models for both isotropic and anisotropic materials to improve the stress-strain prediction of structures subjected to cyclic thermomechanical loads, (2) experimentation to aid in the development and verification of analytical models as well as the development and evaluation of advanced instrumentation, and (3) computations to develop algorithms, advanced numerical techniques, and self-adaptive solution strategies.

ADVANCED COMBUSTOR LINER STRUCTURAL CONCEPT EVALUATION

Advanced combustor liner structural concepts and materials are being tested and analyzed as part of a cooperative program between NASA Lewis Research Center and Pratt & Whitney Aircraft (ref. 12). The integrated and interdisciplinary test/analysis program is conducted for advanced "floatwall" or paneled combustor liner segments. The cyclic tests, conducted in the Structural Component Response Rig, simulate the taxi, ascent, cruise, and descent temperature transients of an engine flight profile by using a computer-controlled quartz lamp heating system. High-quality data bases of liner temperatures and distortions are obtained for calibration and verification of analytical models and computational tools used for predicting the structural response and life of representative liners (fig. 8).

METHODOLOGY OF LEADING EDGE CONCEPT EVALUATION

Leading edges on hypersonic aircraft are subjected to high-heat-flux loads induced by aerodynamic friction. To accommodate this requires advanced high-temperature materials and structural cooling. In response, the Cowl Lip Technology Program is underway to evaluate materials and actively cooled leading edge concepts (ref. 13). The problem is approached through an integrated program of design, analysis, fabrication, and testing (fig. 9). Leading edge concepts are designed, and representative test articles are fabricated from candidate materials including metal and ceramic matrix composites. The articles are tested in a high-heat-flux facility to obtain experimental data for comparison with analytical predictions. The data and analytical predictions provide the basis for assessing the design concept.

ENGINE STRUCTURES COMPUTATIONAL SIMULATOR

A major element of the Computational Structural Mechanics Program (ref. 14) is the development of the Engine Structures Computational Simulator (ESCS). The ESCS, which incorporates discipline-specific methodology and computer codes developed under several research and technology programs, is intended to simulate the structural behavior and performance under test-stand or flight-mission conditions or both. The simulation can be for subcomponents (airfoil), components (turbine blade), subassemblies (rotor sector), assemblies (rotor stage), and up to the entire engine (fig. 10). New design concepts, materials, mission requirements, and so on, can be simulated and their potential benefits evaluated prior to final design and certification testing. Local or component damage effects on engine structural performance can be assessed, and engine structural durability and integrity can be determined. With the availability of this information, the probability of unanticipated failures can be established, and the safety of the engine structure can be assessed.

PROBABILISTIC STRUCTURAL ANALYSIS AND DESIGN METHODOLOGY

The variables of the structural design process (i.e., geometry, material properties, loads, and boundary conditions) are known only with some uncertainty. Although risk necessarily accompanies this uncertainty, an assessment of the degree of risk associated with a design is usually not determined. Rather, the traditional approach is to rely on deterministic design methodology which incorporates some sort of safety factor in an attempt to simply avoid risk altogether. Eliminating risk in a design increases safety and reliability but only at some expense, either in the form of direct cost of production or indirect cost of reduced performance efficiency. In the interest of both safety and economy, then, it is desirable to quantify the effects of uncertainty in a design, and probabilistic design methodology provides the means to accomplish this. This philosophy (fig. 11) is especially pertinent to the design of high-performance, high-energy propulsion systems where mission economy and safety requirements of human-rated vehicles are the two primary (and generally competing) design drivers. In this case the ability to accurately quantify risk is essential to establish an acceptable balance between performance and safety. With this motivation the Structures Division is conducting a comprehensive research program to develop probabilistic analysis and design methodology for propulsion system structures (refs. 15 and 16).

STRUCTURAL TAILORING OF ADVANCED TURBOPROP BLADES

The traditional approach to propeller design has been to satisfy requirements on aerodynamic performance and structural integrity independently through numerous manual design iterations. This process, often conducted by different design groups, is time consuming (expensive), cumbersome (error-prone) and highly subjective (potentially unsuccessful). As a result the process is usually carried out only to the point where a satisfactory design, but not likely the best design, is achieved. The Structural Tailoring of Advanced Turboprops (STAT) computer code (ref. 17) was developed to streamline, automate, and formalize the turboprop design process by incorporating multidisciplinary analysis methodology (aerodynamic, acoustic, and structural) together with numerical optimization techniques, into a computationally effective design system. The system has demonstrated its utility in successful optimizations of large-scale advanced propfan designs to achieve reductions of several percent in aircraft direct operating cost (fig. 12).

CONCLUDING REMARKS

A cursory overview has been presented of several research activities currently underway in the Structures Division of the NASA Lewis Research Center. From these efforts, promising technologies are emerging which will better enable the structural engineer to conduct the complex analyses required to provide improved designs for aerospace propulsion system structures.

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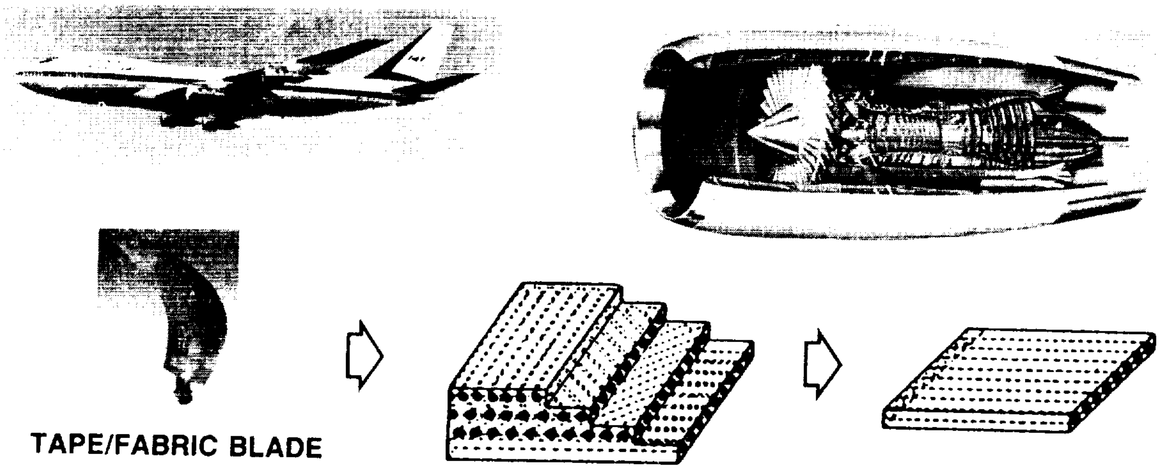

ICAN COMPARISON

LONGITUDINAL ELASTIC MODULUS, ksi						
	EXPERIMENTAL			ICAN PREDICTIONS		
LAMINATE MATERIAL	−300 °F	70 °F	200 °F	−300 °F	70 °F	200 °F
7781E-GLASS CLOTH	4600	4370	3970	4589	4251	4076
7576E-GLASS CLOTH	6540	6020	6050	5587	5395	5457
REPRESENTATIVE	5320	4370	4150	4440	4114	3948

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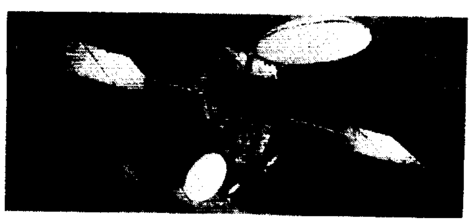
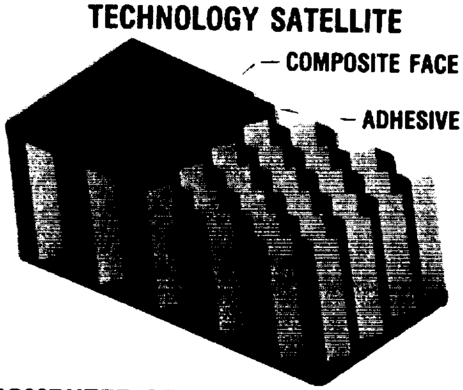
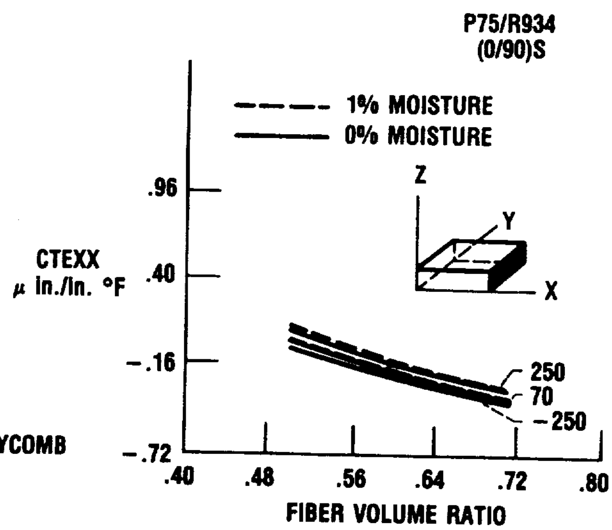
Figure 1. - Integrated Composites Analyzer (ICAN).



ACTS ADVANCED COMMUNICATION TECHNOLOGY SATELLITE



COMPUTER-GENERATED MODEL OF THE STRUCTURE USED FOR THE ANALYSIS



COEFFICIENT OF THERMAL EXPANSION AS A FUNCTION OF FVR AND HYGROTHERMAL CONDITIONS

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Figure 2. - Composite sandwich structural simulation for satellite antenna reflectors.

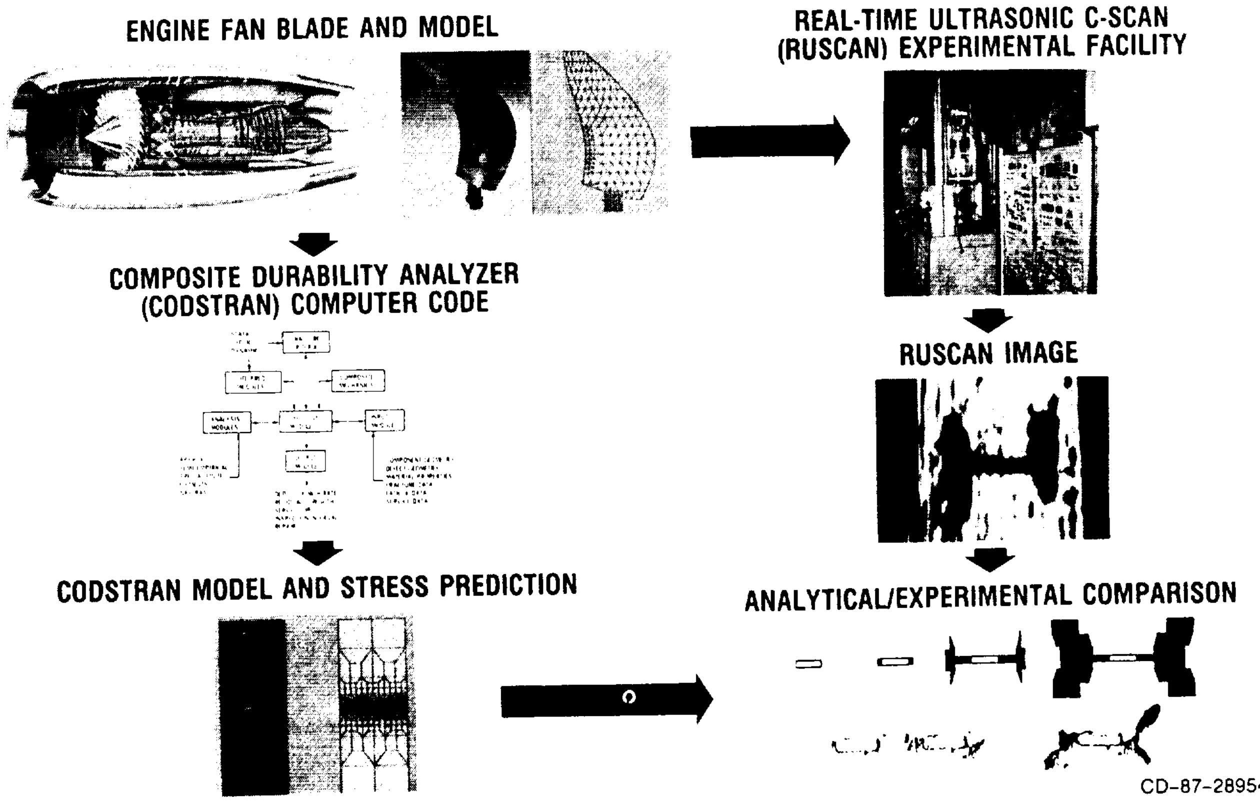

Figure 3. - Comprehensive analytical/experimental evaluation of composite durability.

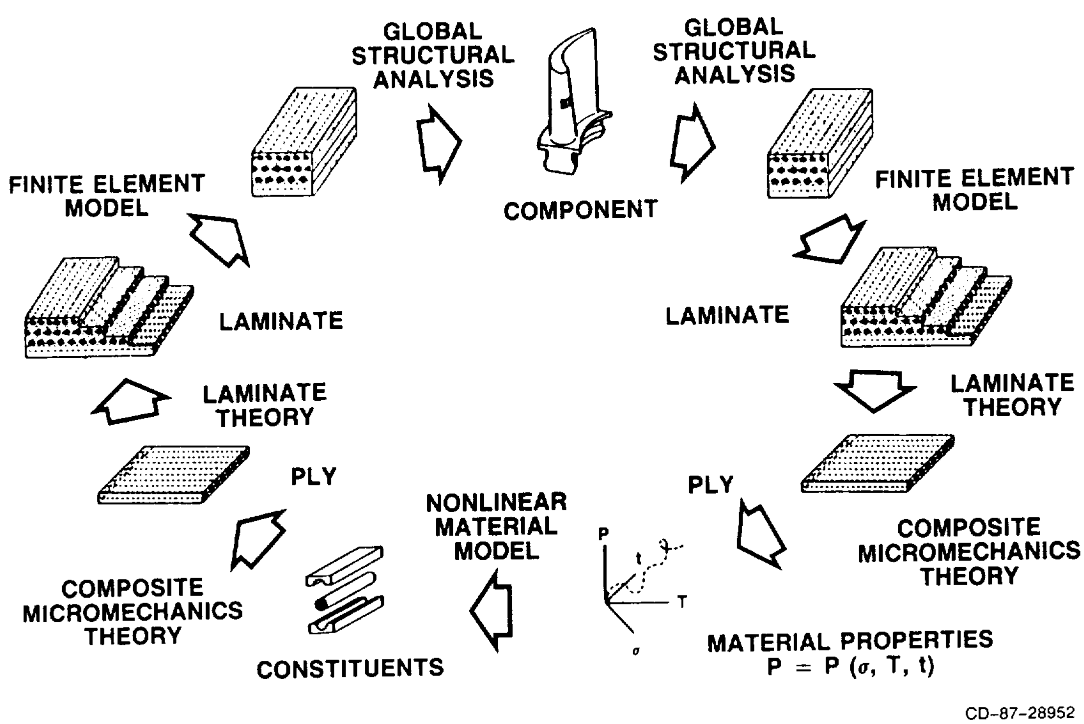

Figure 4. - Integrated approach to structural analysis for high-temperature composites.

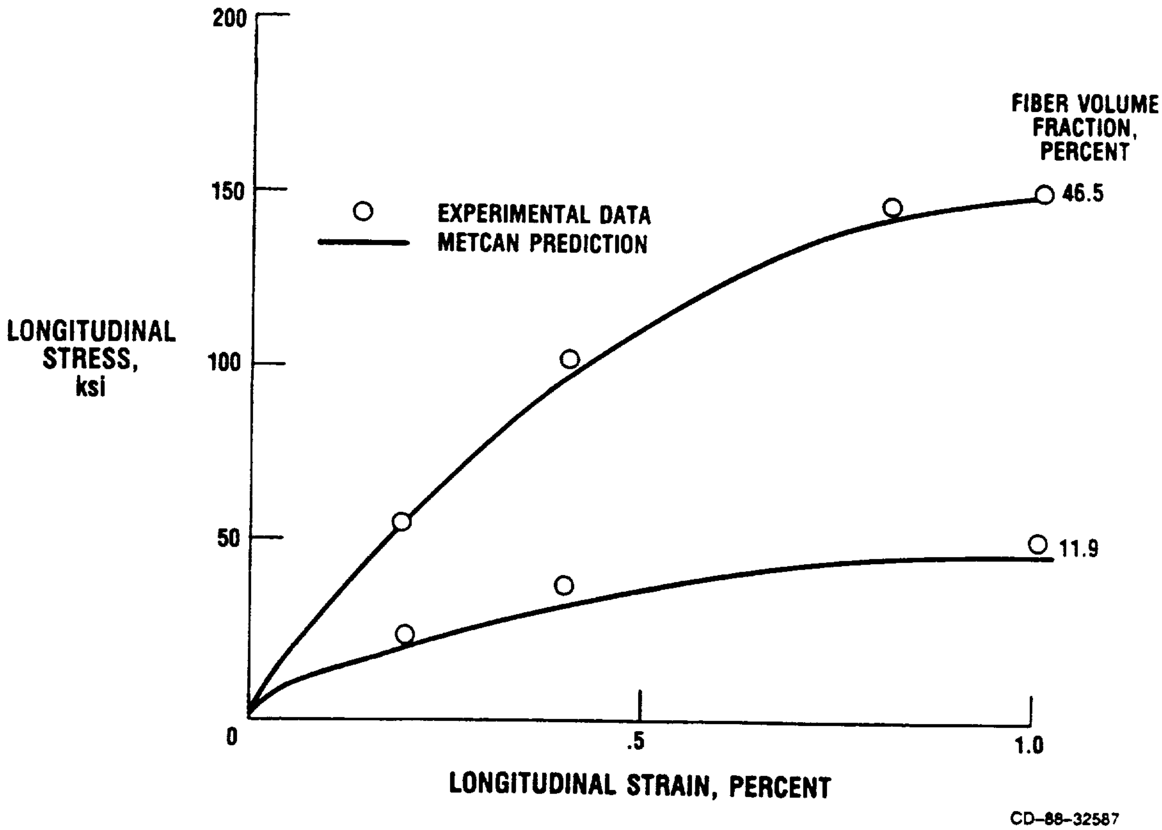

Figure 5. - Nonlinear, monotonic stress-strain response of unidirectional tungsten/copper composite.

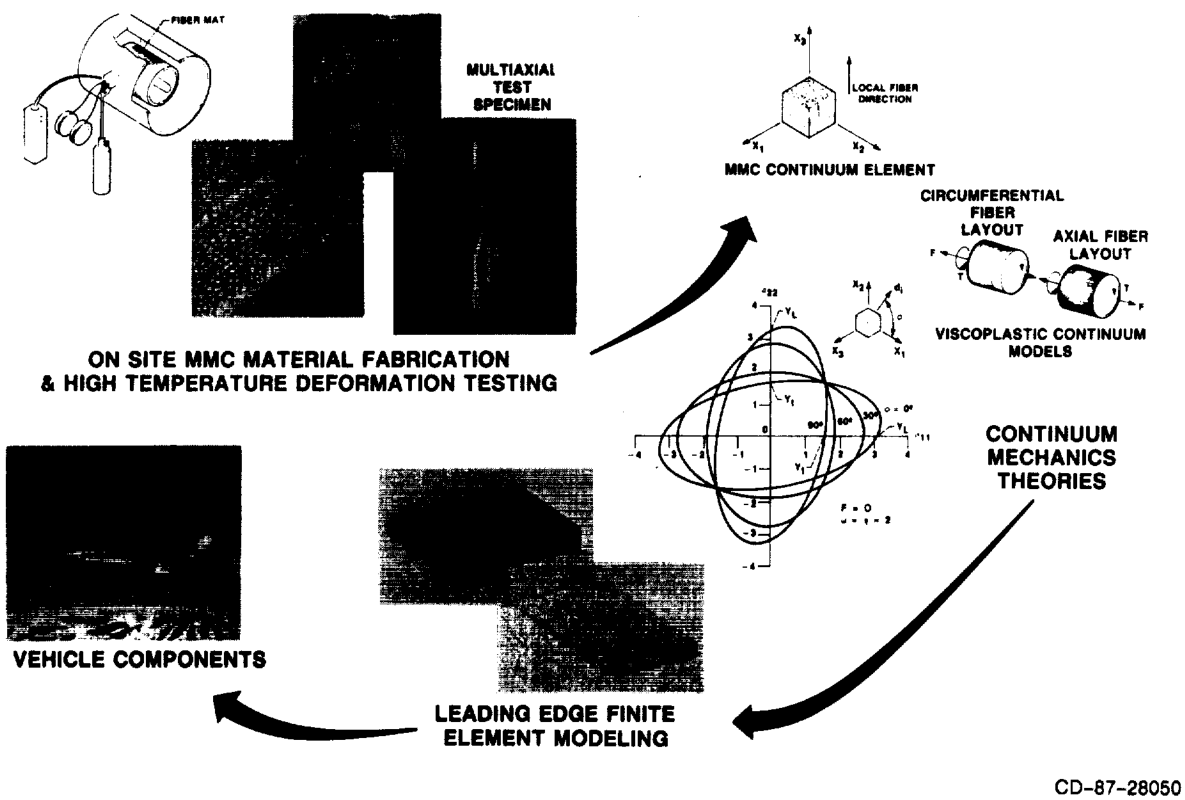

Figure 6. - Lewis' unique role in metal matrix composite technology development.

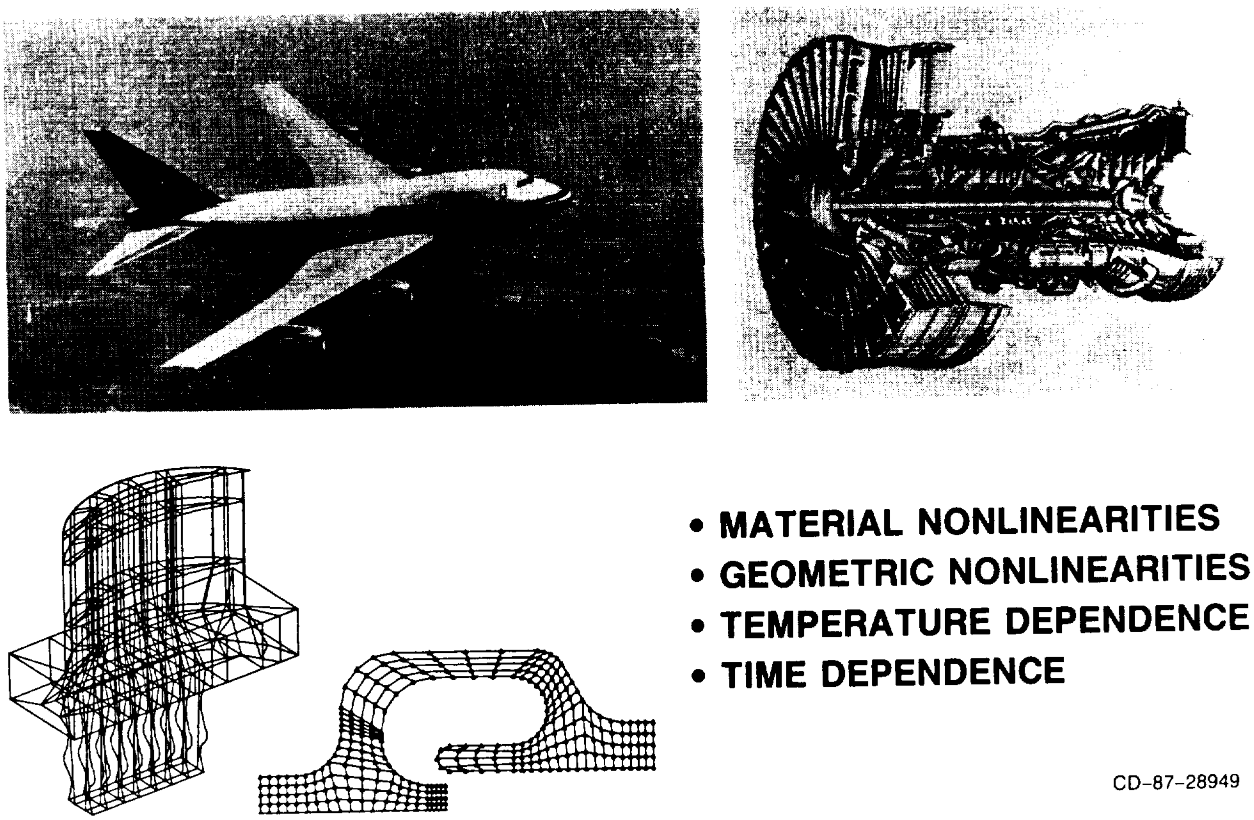

Figure 7. - Advanced inelastic structural analysis methods.

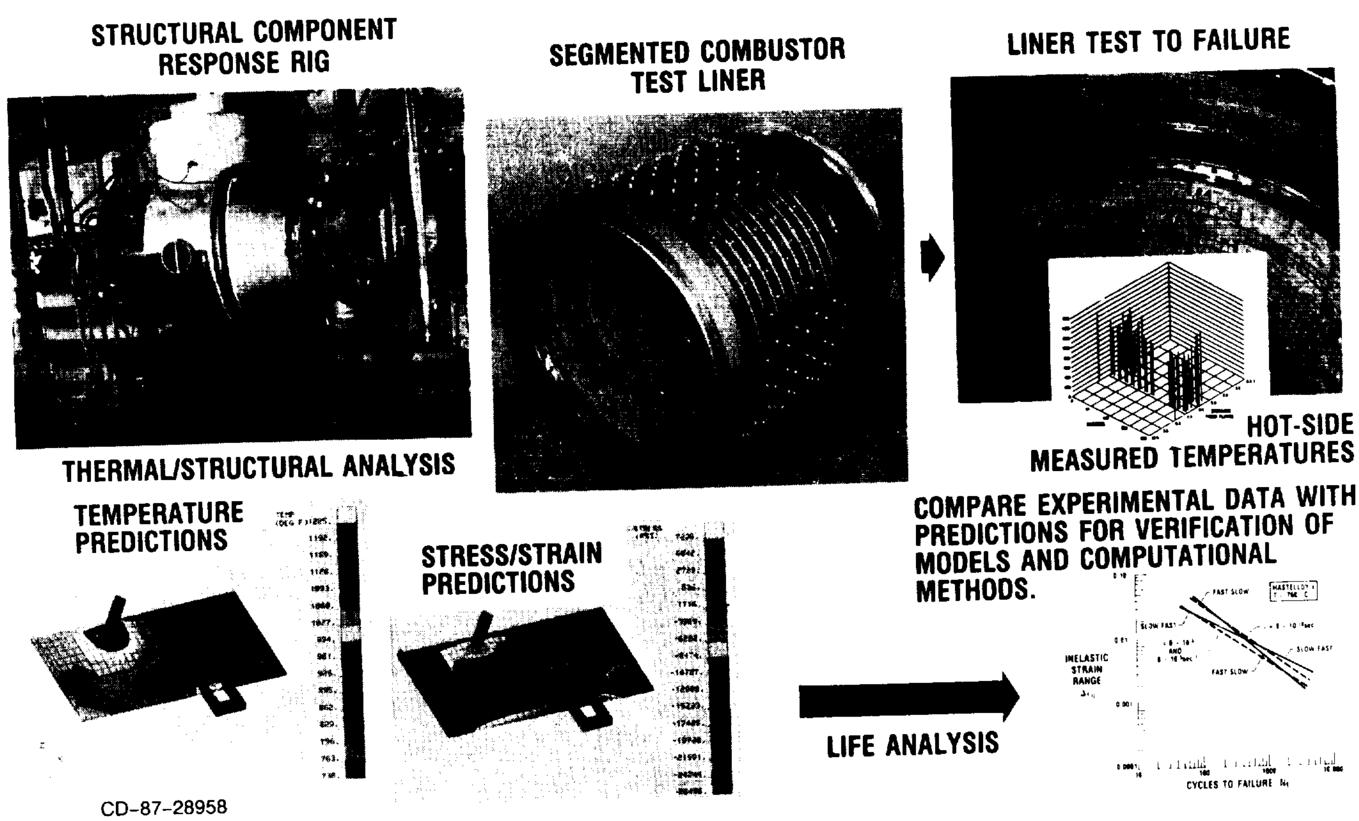

Figure 8. - Advanced combustor liner structural concept testing and thermal/structural/life analysis.

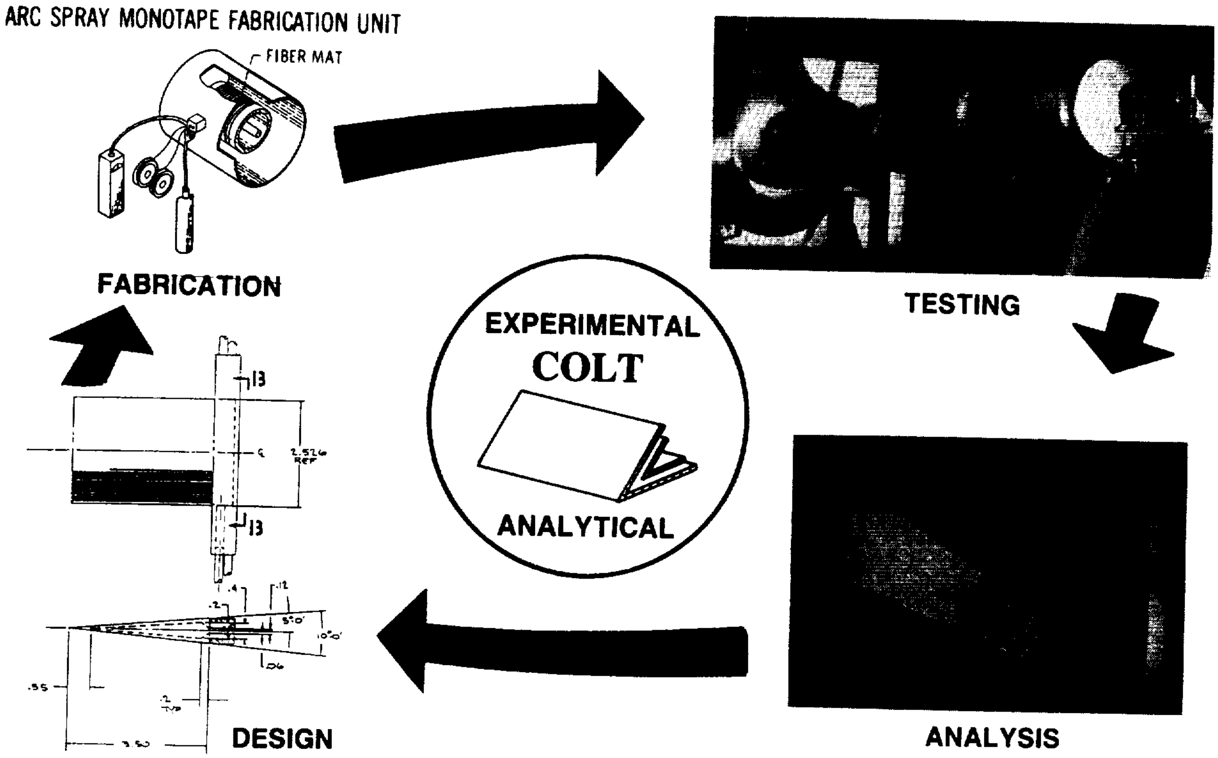

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Figure 9. - Methodology of leading edge concept evaluation.

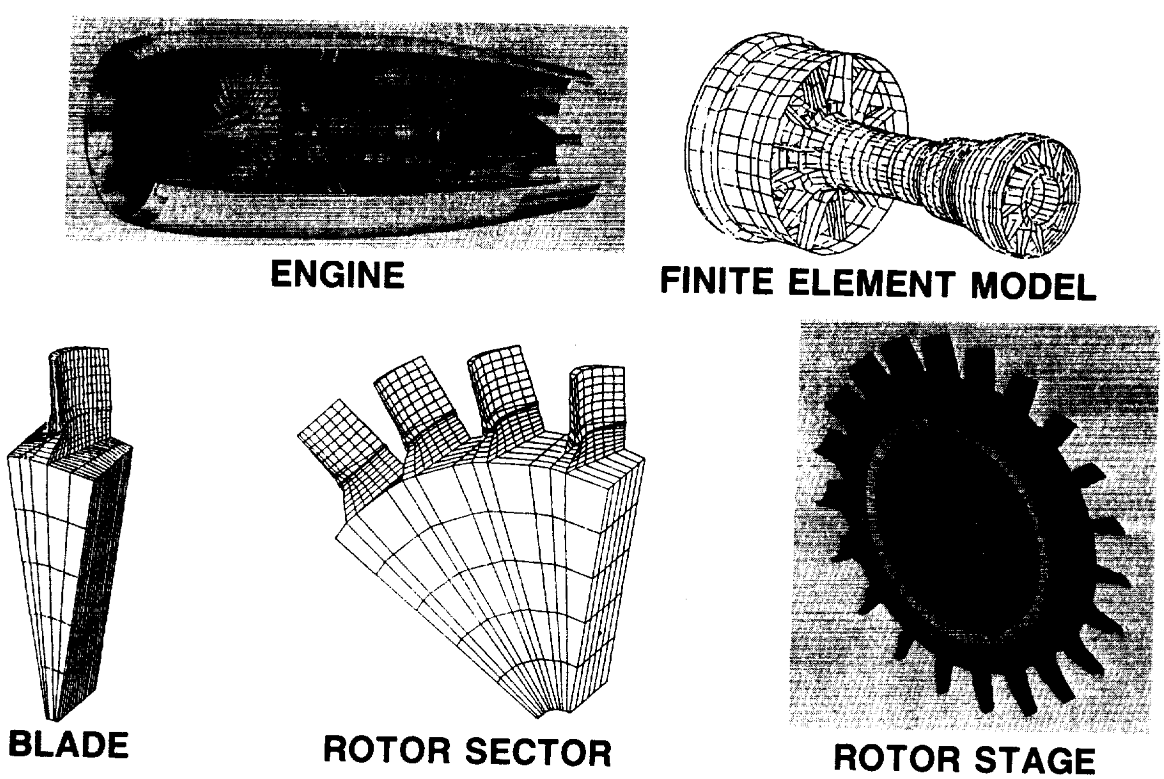

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Figure 10. - Engine Structures Computational Simulator.

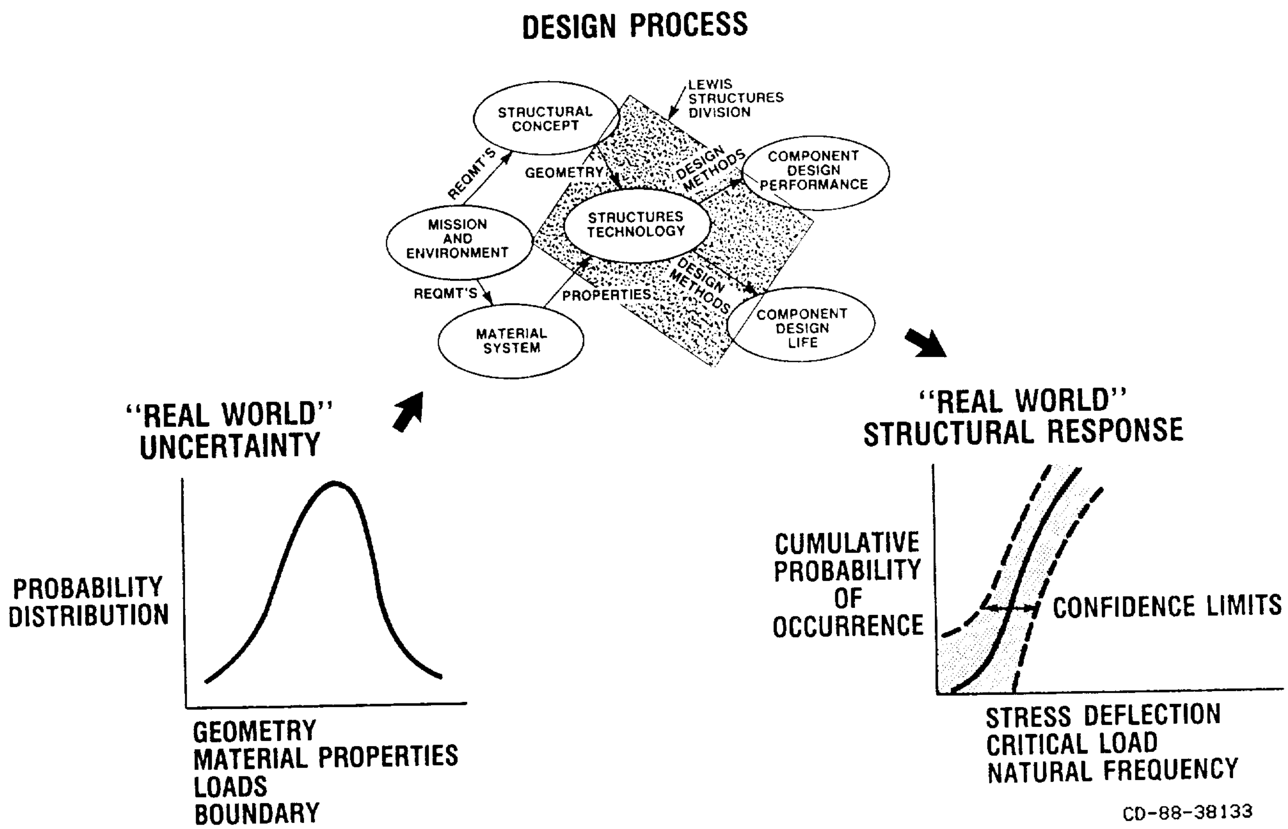

Figure 11. - Probabilistic Structural Analysis/Design methodology.

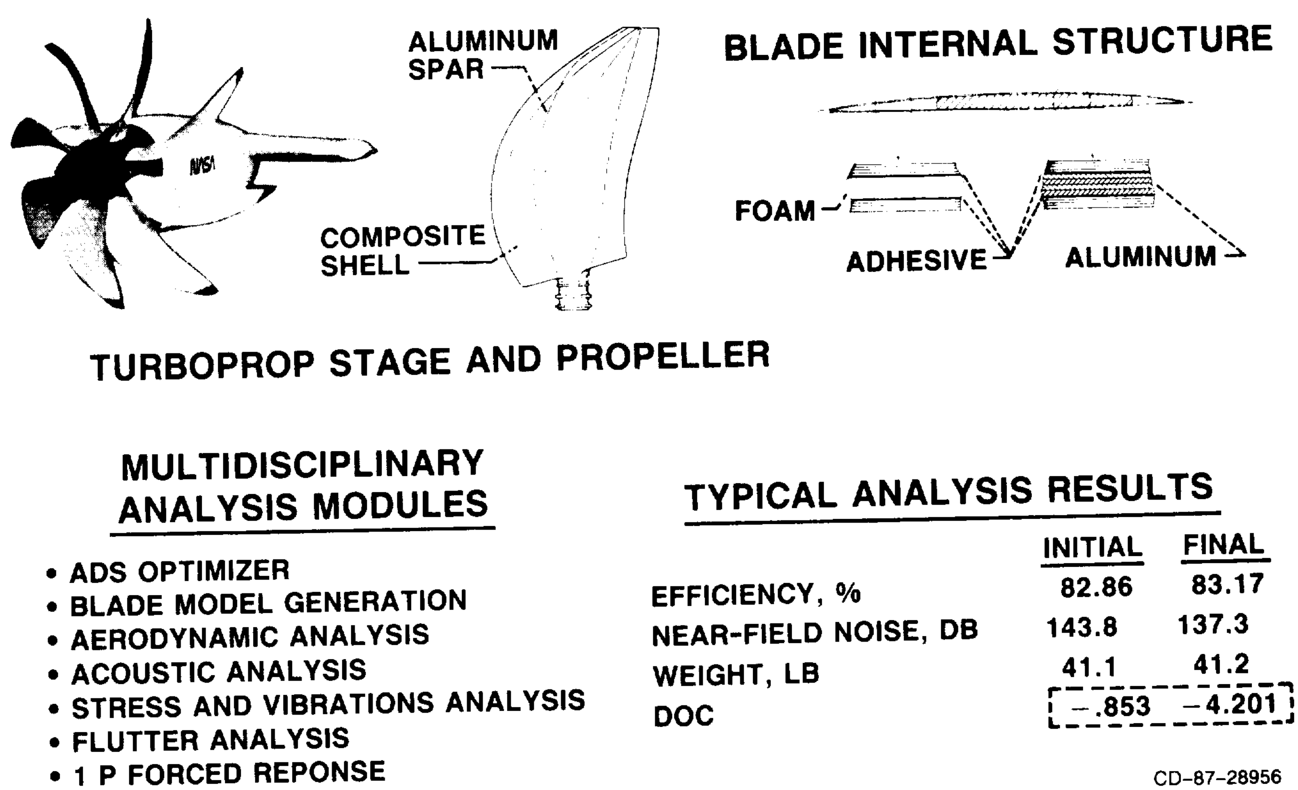

Figure 12. - Structural tailoring of advanced turboprops.